２０１４年度　先端数理科学研究科
博士学位請求論文（要旨）

A study on pattern formation in crowd dynamics via mathematical modeling
（群集ダイナミクスにおけるパターン形成の数理モデリングによる研究）

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内 容 の 要 旨

1. 本研究の問題意識と目的

In this study the investigation of self-organized pattern formation in crowd dynamics with mathematical modeling is presented. Crowd systems are examples of non-equilibrium particle flow and show spontaneous collective motion. It is important to clarify the mechanism, to investigate the universality, and to establish the mathematical way to analyze the discrete flow. Based on these backgrounds, the main focus is placed on some self-organization phenomena in active particle systems that correspond to crowd motion. Through the modeling, analysis and simulation, some of the spontaneous pattern dynamics will be explained. Through this work, I also would like to demonstrate that the mathematical modeling is a useful tool for the investigation of pattern formation in active particle flow in which the conventional fluid approximation does not hold. Many of the previous studies are based on case studies using numerical simulations and dedicate to find new self-organized phenomena. As a result, the clarification of the underlying mechanism draws less attention of crowd scientists. One of the reasons of this drawback is the absence of an appropriate description method to investigate the collective motion of spontaneous order in dissipative particle systems. Here I would like to stress that the mathematical modeling could be a useful method in crowd studies. The combination of simulations, modeling and its analysis offers us the revelation of the fundamental mechanism of crowd motion and new insights into the pattern dynamics in discrete flow, as shown in this study.

２．本研究の構成ならびに各章の要約

This study is composed of (i) historical survey of collective motion of self-driven particles, (ii) technical reviews with particle simulations, (iii) modeling self-organized phenomena, (iv) analyzing the model to clarify the mechanism of the phenomena, and (v) comparisons of the modeling results with the simulation results.

Chapter 1 is the introduction of crowd dynamics. The purpose of the study is to give mathematical descriptions for some self-organized phenomena in crowd dynamics and provide its possible mechanisms. Crowd dynamics is a discipline that treats spontaneous order in the flow of human mathematically. It is well known that crowd shows spontaneous collective patterns. Interestingly, some patterns in crowd motion show the phase transition, for instance, from fluid-like to solid-like configuration, depending on the density, noise and driving forces. Some of them are specific to crowd motion, on the other hand, some others are universal since similar patterns are observed in totally different systems. Comparison of the differences and the similarities will give us new insights into the collective motion. Another importance of studying crowd motion is that crowd dynamics provide a new challenging issue: how should we describe and understand discrete particle flow? The numerical many-particle calculations do not necessarily lead deeper understanding of complex phenomena. Here we need to seek an alternative method to describe particle flow. The study of crowd dynamics would give a new example of transition phenomena and offer an opportunity of developing new type of mathematical description of pattern dynamics. In this chapter, historical review is also provided. Crowd dynamics has a long history, multiple viewpoints and plenty of contributions to today's crowd sciences. This review is based on the standpoint of self-organization in crowd systems. Finally, the critical discussion on crowd dynamics is given. Note that modeling crowds via physics-based concepts only holds when we consider (i) panic situations, (ii) each person in a crowd have their definite destinations but the ways to reach there are less conscious, and (iii) the size of crowds is tremendously large. In such situations, the difference of each people diminishes and the averaged behavior could be treated statistically.

Chapter 2 is the reviews of the spontaneous phenomena observed in crowd dynamics It is well known that the crowd motion is accompanied by self-organized order. Here I would like to show the examples, fundamental features, and detailed historical reviews for some phenomena in crowd dynamics. The discussion provided here is mainly based on the social force model. The phenomena discussed here are as follows: (1) lane formation in pedestrian counterflow in a narrow corridor, (2) the freezing-by-heating transition, (3) self-excited oscillatory flow at bottlenecks, (4) the faster-is-slower effect in bottleneck particle flow.

Chapter 3 gives a mathematical model of oscillatory pedestrian flow. I investigate the oscillatory pedestrian flow via mathematical modeling. This ``pedestrian flow oscillator'' has been observed both numerically and experimentally and known as an example of self-organized order in pedestrian systems. In this chapter, I construct a model that describe the oscillatory flow and investigate its mechanism. Through an analysis of the model, I show that the oscillator is identified as a van der Pol-type self-excited oscillation.

Chapter 4 dedicate to an analytical investigation of the faster-is-slower effect with a simplified phenomenological model. I investigate the mechanism of the phenomenon called the faster-is-slower effect in pedestrian flow studies analytically with a simplified phenomenological model It is well known that the flow rate is maximized at a certain strength of the driving force in simulations using the social force model when we consider the discharge of self-driven particles through a bottleneck. In this study, I propose a phenomenological and analytical model based on a mechanics-based modeling to reveal the mechanism of the phenomenon. I show that our reduced system, with only a few degrees of freedom, still has similar properties to the original many-particle system and that the effect comes from the competition between the driving force and the nonlinear friction from the model. Moreover, I predict the parameter dependences on the effect from our model qualitatively, and they are confirmed numerically by using the social force model.

Chapter 5 explains the dynamic structure in pedestrian evacuation with the aid of image processing approach. I show that there exists a typical dynamic arch-shape structure in pedestrian evacuation system governed by the social force model It is well known that the simulation of pedestrian evacuation from a square room using the social force model shows arch-shape formation and clogging in front of the exit. It is also known experimentally and numerically that an obstacle near the exit could improve the flow rate, but detailed mechanism of this effect is not clear. In this paper, I show the existence of the ``dynamic arch,'' the typical structure in the long term, by using the social force model and the image processing. The time-averaged image of the system shows us the existence of the typical structure in the system and it can be interpreted as the probability distribution of the arch formation. With this method, I discuss the possible physical mechanism of the effect of an obstacle in the pedestrian system. From the observation of the morphological feature of the arch obtained by the simulation and image processing, I show that the obstacle affects the structure of the arch in three ways. These effects could lead the easy-to-break arch that enhances the flow rate of the system.

Chapter 6 is the conclusion. The study stresses that the mathematical modeling could be a useful method in crowd studies. The combination of simulations, modeling and analysis offers the revelation of the fundamental mechanism of crowd motion and insights into the pattern dynamics in discrete flow.